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Coherent charge qubits based on GaAs quantum dots with a built-in barrier

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Abstract. We investigated using as basic elements of the quantum computer — quantum bits (qubits) semiconductor quantum dots containing one electron and consisting each of two tunnel-connected parts, as shown in Fig. 1. The numerical solution of a Schrödinger equation with the account of Coulomb field of adjacent electrons shows, that in such structures the realization of a full set of basic logic operations which are necessary for fulfillment of quantum computations is possible. Decoherence rates due to spontaneous emission of phonons and acoustic phonons (both piezoelectric and deformational) are evaluated. Durations of one- and two-qubit operations versus qubit geometry are obtained.

1. Introduction

Quantum computing attracts much attention recently because it allows solving some classical problems by using quantum algorithms for exponentially smaller (depending upon length of input data) number of steps compared with the best classical algorithms. A. Ekert *et al.* [1] proposed using as qubit basis states ("0" and "1") the two states of spatial quantization of one-electron semiconductor quantum dot. Unfortunately they found soon [2] that their proposal could not be a real qubit because of low coherence of such system. For realization of bi-qubit operations the authors of [1, 2] have offered to use electrical dipole interaction. Potential in one of these quantum points thus was guessed by asymmetric. Distance between dot states was 10–100 meV. The variants of such structures despite of their intrinsic decoherence were studied further by other groups of researchers [3, 4].

In this work we propose to use as qubit quantum dot with a symmetric lateral view, as shown in Fig. 1.

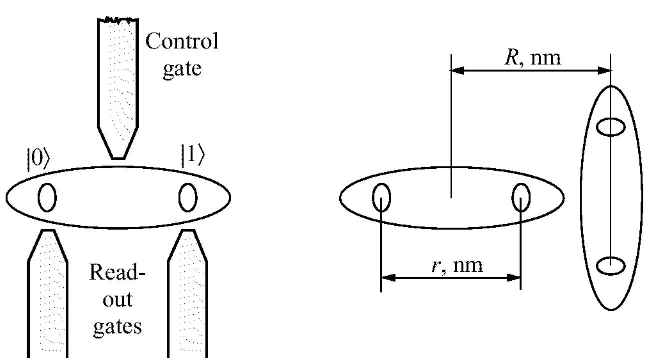

Fig. 1. Sketch of quantum bit (left) and sketch of CNOT gate (right).

2. Qubit structure

To avoid high decoherence rates we propose to use special constriction potential for each dot. The presence of two minimums of potential, disjointed by thick barrier is essential. It is supposed that there is only one electron in each qubit. Presence of the second electron is excluded by Coulombic interelectronic repulsion. We conduct hereinafter evaluations for gallium arsenide quantum dots. At distance between minimums $r = 10\,\text{nm}$ (see Fig. 1) the Coulomb energy will be about $e^2/\kappa r = 11\,\text{meV}$, that allows to eliminate spontaneous charging of a point by the second electron. To obtain clock rates and other performance parameters of qubit offered we numerically solved a two-dimensional Schrödinger equation for an electron in a GaAs quantum dot with potential V,

$$V = \frac{m\omega^2}{2}\left(x^2 + y^2\right) + V_{\text{B}} \exp\left(-\frac{x^2}{W^2}\right) \tag{1}$$

where $m = 0.067m_e$, $W = nl$, $\omega = \hbar/ml$, $V_{\text{B}} = 1.510^{-19}\,\text{J}$, $l = 20\,\text{nm}$, n varies within the range 0.095–0.35.

For logical "0" and "1" it is convenient to take not states with particular energy (Ψ_1 and Ψ_2), but their Hadamard transform

$$|0\rangle = \frac{\Psi_1 + \Psi_2}{\sqrt{2}} \qquad |1\rangle = \frac{\Psi_1 - \Psi_2}{\sqrt{2}}$$

It allows to record input data and read out results by single-electronics procedures by using read-out gates, as shown in Fig. 1. The central control gate serves for lowering of a potential barrier to perform quantum unitary transformations.

3. Basic unitary transformations

Let the qubit be in state Ψ_0

$$\Psi_0 = c_0\,|0\rangle + c_1\,|1\rangle$$

When a barrier is high, two states evolve with one frequency ω_1, as two lower states are practically merged.

$$\Psi(t) = (c_0\,|0\rangle + c_1\,|1\rangle)\exp(i\omega_1 t)$$

The lowering of a barrier leads to an inequality of frequencies ($\Delta\omega = \omega_2 - \omega_1 > 0$) and to periodic gyration of a vector of a qubit state in basis $\{|0\rangle, |1\rangle\}$.

$$\Psi(t) = \frac{1}{\sqrt{2}}\left[c_0\cos(\Delta\omega t/2) + c_1\sin(\Delta\omega t/2)\right]\exp\left[\frac{i(\omega_1 + \omega_2)t}{2}\right]$$

Having given an impulse of a positive voltage of particular duration τ_{NOT}, equal to $\pi/\Delta\omega$, we (throwing away an incidental phase factor) unitary transform a qubit into state

$$NOT(\Psi_0) = c_1\,|0\rangle + c_0\,|1\rangle$$

So, with the help of the given procedure it is possible to exchange amplitudes at 0 and 1, that is to realize the unitary operation NOT. Changing a pulse length it is possible to realize qubit rotation by any required angle.

For build-up of the universal quantum computer it is necessary also to know how to realize one nontrivial two-qubit operation (not decomposable in a sequence of one-qubit

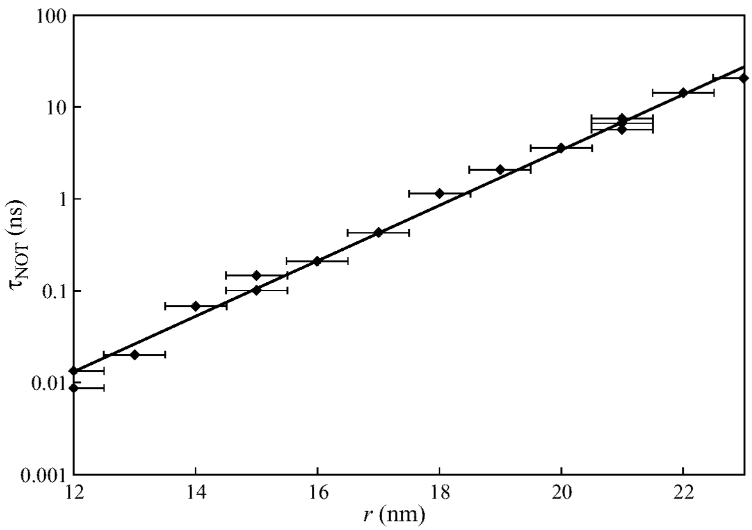

Fig. 2. Duration of NOT operation vs r.

ones). We consider realization of the operation CNOT. Depending on a state of control qubit, target qubit should stay the same or be reversed after CNOT transform (i.e. we should apply to target qubit operation of identity or NOT). For realization of a two-qubit CNOT operation between adjacent qubits we use a Coulomb interaction. Let's arrange two qubits as shown in Fig. 1. It is supposed that there is completely opaque barrier between qubits. Height of a barrier dividing right (target) qubit, depends on a state of left-hand (control) qubit. Having slightly opened the barrier in target qubit with the help of corresponding central gate it is possible to achieve realization above operation, i.e. the operation of identity, when control qubit is in a state 0 and operation NOT, when control qubit is in a state 1, that is operation CNOT. It is achieved by varying pulse duration so that if control qubit is "0", then the action of an impulse is equivalent to sequential application even number of operations NOT to target qubit, that is operation of identity. If control qubit is "1", then the action of an impulse is equivalent to sequential application odd number of operations NOT to second qubit, that is operation NOT.

4. Qubit modelling

While modelling, the qubit-qubit interaction was calculated directly from a Coulomb's law (in all nodes of a two-dimensional grid the field influencing target electron due to a partial charge of control qubit electron from all other nodes of a grid was evaluated). Exchange effects were neglected. The dependences of durations of operation NOT, depending on geometrical parameters are shown in Fig. 2. While estimating a coherence of proposed structure, we have considered a low-temperature limit ($T \to 0$). It is justified, as the modern cryogenic engineering allows to realize operations of structures at temperatures down to several millikelvins, that is sufficienlty lower than the distances between the basic and first excited levels in qubits. The case of high temperatures is not favourable for qubits because of inevitable prompt losses of a coherence and impossibility of correct operation of the quantum computer. However, in solid-state structures even at absolute zero of temperature the processes of losses of a coherence owing to a spontaneous emission of quantums or acoustic phonons and transition of an electron from excited on a ground

level are possible. These processes also will limit a degree of a coherence in our structure. We considered spontaneous radiation of quanta and acoustic phonons (both due to deformational and piezoelectric electron–phonon interaction), spontaneous radiation of a ultrasonic deformation phonon, spontaneous radiation of a ultrasonic polarization phonon. The dominant mechanism of losses of a coherence occurred to be the emission of polarization acoustic phonons. However, our calculations show that even this process has small probability at of clock tick relevant to clock rates for wide structures (wider 15 nm).

So, new quantum bit is offered, on the basis of electrons in symmetric semiconductor quantum points controllable with the help of voltages on electrodes. The frequencies of switching of the quantum register lay in convenient for electronic control range and reach 1 GHz. The offered quantum register is controllable and scalable.

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